

GRANT
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Princeton University Observatory

PEYTON HALL

PRINCETON, NEW JERSEY 08544

August 12, 1992

Dr. Derek Buzasi
Science Operations Branch, Code SZE
Astrophysical Division
NASA
Washington, DC 20546

10P

Dear Dr. Buzasi:

This letter represents our final report on Astro Theory Grant #NAGW-765, "The Universe at Moderate Redshift," covering the period March 1, 1988 through February 28, 1991.

1) RESEARCH

The focus of our research effort over this interval was stated recently in a form that is remarkably accurate:

The Universe at small redshift shows diverse structures on all measured scales. But at the era of decoupling, at a redshift of $z = 10^3$, the Universe was extremely smooth and featureless. The central question addressed in this proposal is "How did the observed structure develop?" NASA has begun a program which in this decade and the next will launch several major observatories - HST, AXAF, COBE, GRO, SIRTf and LYMAN/FUSE - that will push the observational curtain further back, to $z > 2$ for galaxies and $z > 5$ for quasars. With the better observational input and the rapid theoretical developments over the last ten years serving as a basis, we propose to perform at Princeton coordinated studies which combine model making with theoretical analysis of observations in order to outline and understand the physical processes acting during epochs of moderate redshift. In addition, we intend to show how better space measurements of the radio, x-ray and γ -ray backgrounds will severely constrain theories for the origin of structure.

We plan to divide the program into four major overlapping scientific areas: galaxy formation and the development of large scale structure, the intergalactic medium and background radiation fields, quasar statistics and evolution and, lastly, gravitational lensing. Aided by two graduate students and two postdoctoral fellows to be supported by the grant and occasional senior visitors to be supported by Princeton University funds, we propose to make major computer simulations using a powerful departmental CONVEX C-220 minisupercomputer in each of these areas as well as more traditional theoretical analyses, with the ultimate purpose of helping to define the physical causes of cosmic structure.

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Well, what have we achieved? The attached bibliography (Attachment A) of 61 papers published in refereed literature during the interval covered provides the most important measure of our work. However, it is useful to list here some of the highlights.

A) Galaxy Formation and Large-Scale Structure

Gott and collaborators developed and applied an ingenious new measure of the topology of large-scale structure. The "genus" tells qualitatively whether the structures described are more like (if you will excuse the food metaphors) Swiss cheese (hole dominated), meatballs (peak dominated), or sponge cake (interconnected matter and interconnected holes). Genus has turned out to be an important discriminant among theories and has been widely used. With it one can reject some versions of the explosive picture and some versions of the non-gaussian seed picture for the formation of cosmic structure.

Gunn, collaborators and students have worked on galaxy formation directly using the SPH numerical scheme and other techniques. They have shown how many of the observed properties of galaxies (including the disk-bulge dichotomy) can be understood in terms of the CDM scenario. Ostriker and collaborators worked primarily to develop an accurate three-dimensional Eulerian hydrocode, which could model directly the development of large-scale structure, allowing for the detailed atomic physics of a variety of processes, both collisional and radiative. Output of the code can be directly compared with ROSAT x-ray maps or COBE microwave maps. In both cases, it has been found that emission from hot gas, caused by the formation of large-scale structure, will give a detectable signal.

B) Intergalactic Medium and Background Radiation Fields

Ostriker and collaborators showed that the decrease in the number of Lyman-alpha absorption line systems, which is apparent as one approaches a quasar, could be interpreted simply as a "proximity effect," due to the extra ionizing radiation in the immediate neighborhood of the quasar. This enabled them to estimate the background radiation field at $J_\nu = 10^{-21}$ ergs/hz/sec/steradian/cm² in work which has been confirmed by a number of independent studies. This conclusion implies that, either there are more quasars at moderate redshift than shown by current surveys or that young galaxies emit significant amounts of ionizing ultra violet radiation.

C) Quasar Statistics and Evolution

Turner and collaborators have attempted to understand the x-ray counts of quasars and how they can be made consistent with recently compiled optical quasars. If they used the previously determined x-ray to optical spectral index of the optically selected QSO sample and the BSP optical QSO counts, they found a large excess in predicted x-ray sources compared to observations by Einstein satellite. They therefore used the x-ray observations to constrain the QSO x-ray properties and their evolution using a linear parameterisation between $\text{Log}(L_x)$, $\text{Log}(L_{\text{opt}})$, and $\text{Log}(1+z)$. Best agreement with all the observational constraints was obtained for a negative redshift evolution and a decreasing L_x/L_{opt} with optical luminosity. For these fit parameters, they predict a total contribution to the cosmic x-ray background at 2keV of 30% from BSP sample QSOs at $B < 21$ and $z < 2.2$.

D) Gravitational Lenses

Paczynski and collaborators showed how the variation in the brightness observed in "Huchra's lens" ASO2237+0305 could be understood in terms of the matter distribution within the intervening galaxy.

Turner has carried out reviews of the evidence that undetected gravitational lensing events are significantly influencing quasar population statistics and of the evidence for dark matter in gravitational lenses. In the former case, the primary conclusion was that the possibility cannot yet be ruled out although available evidence suggests that the effect is not too important for quasars in general. Some special subsamples of quasars may well be affected. In the latter case, individual cases of lensing suggest that the gravitational potential wells associated with galaxies are sometimes deeper than generally believed, the indication that the center of the dark matter distribution in some systems does not coincide with the center of light, and the existence of dark objects with mass-to-light ratios substantially larger than those associated with galaxies and galaxy clusters.

II) EDUCATION AND TRAINING

During the period covered by the grant, we have employed (with whole or partial support from NAGW-765) nine postdoctoral fellows, 12 graduate students and one undergraduate. Incidentally, the list includes three female scientists. All of those employed have been able to use the knowledge and training received here to continue with more advanced scientific and technical jobs. The postdoctoral fellows with current affiliations (given in parantheses) are as follows:

Postdoctoral Fellows

S. Bajtlik (Copernicus Astron. Center., Poland)
D. P. Bennett (Lawrence Livermore National Laboratory)
R. Cen (Princeton Univ.)
A. Chokshi (Caltech, IPAC)
R. C. Duncan, Jr. (U. of TX)
L. E. Hernquist (UC-Santa Cruz)
R. Juskiewicz (Copernicus Astron. Center., Poland)
M. Panek (Copernicus Astron. Center., Poland)
Y. Pei (Princeton Univ.)

The following graduate students received support from this grant:

Former Graduate Students

A. Babul (Cambridge)
R. Cen (Princeton U.)
M-H Lee (CITA, Toronto)
K. R. Long (U. of MA)
J. Escudé-Miralda (Cambridge Univ.)
C. Park (Caltech)
A. C. Thompson (CITA, Toronto)

Current Graduate Students

X. Huang (Princeton U.)
S. Mao (Princeton U.)
S. Malhotra (Princeton U.)
A. Stone (Princeton U.)
G. Toth (Princeton U.)

III) COMMUNICATIONS

In addition to the published results, we have sponsored conferences (as described in our "Management Plan" to coordinate with observers and help in the dissemination of the theoretical research results. As the most recent example of this type of activity under the auspices of the grant, D. N. Spergel organized a conference on the implication of COBE's detection of the

microwave background fluctuations for cosmology. This conference, organized after the COBE announcement, was held on June 12 and 13, 1992, in Princeton and attended by over 100 scientists and students. Despite the fact that the conference was organized in less than one month, many leading scientists from the United States, France, Italy, the UK, Switzerland, Japan, and the Former Soviet Union were able to participate.

Since the conference was the first meeting on this subject immediately after the COBE announcement, it was an important forum for discussion of the COBE results. Many members of the COBE science team attended the meeting and they were able to present a more detailed account of their work to this specialized meeting than at the APS meeting. In addition to the COBE team, there were representatives from nine other CBR experimental groups who presented progress reports at the meeting. Theoretical discussions focused both on the implications of these detections for the inflationary scenario and for various models for the formation of large-scale structure.

The meeting also served an important educational role. Seventeen graduate students from Princeton, Columbia and University of California attended the meeting. Several journalists, including reporters from *Time*, *The New Yorker*, *Science*, and the *Los Angeles Times*, also attended the meeting.

We were able to cover all the costs for the meeting from registration charges and departmental sources, so there was no charge to the grant for this conference.

The overview and attachment should give an impression, but only an impression, of the great deal of frontier work performed under this grant.

Sincerely yours,

Jeremiah P. Ostriker

JPO/imr

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cc: NASA Sci. & Tech. Info. Fac.

J. RICHARD GOTT

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